



## Article

# A New Framework to Evaluate Urban Design Using Urban Microclimatic Modeling in Future Climatic Conditions

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**Abstract:** Building more energy-efficient and sustainable urban areas that will both mitigate the effects of climate change and anticipate living conditions in future climate scenarios requires the development of new tools and methods that can help urban planners, architects and communities achieve this goal. In the current study, we designed a workflow that links different methodologies developed separately, to derive the energy consumption of a university school campus for the future. Three different scenarios for typical future years (2039, 2069, 2099) were run, as well as a renovation scenario (Minergie-P). We analyzed the impact of climate change on the heating and cooling demand of buildings and determined the relevance of taking into account the local climate in this particular context. The results from the simulations confirmed that in the future, there will be a constant decrease in the heating demand, while the cooling demand will substantially increase. Significantly, it was further demonstrated that when the local urban climate was taken into account, there was an even higher rise in the cooling demand, but also that a set of proposed Minergie-P renovations were not sufficient to achieve resilient buildings. We discuss the implication of this work for the simulation of building energy consumption at the neighborhood scale and the impact of future local climate on energy system design. We finally give a few perspectives regarding improved urban design and possible pathways for future urban areas.

**Keywords:** climate change; energy system sizing; sustainable urban planning; urban climate; urban design

## 1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) stated in their last report that anthropogenic greenhouse gases are responsible for the current climate change [1]. Urban areas are responsible for more than 70% of the emissions with over half of the world population living in urban areas. It is hence crucial to develop more sustainable urban areas that will significantly reduce the carbon footprint of cities while at the same time taking into account the rising temperatures and the vulnerability of the urban spaces.

In recent years, we have been confronted with diverse mitigation and adaptation strategies, emphasizing the idea that urban areas need to be modified to cope with both climate change and urban heat islands. While mitigation tries to reduce the impact that can lead to higher energy consumption and emissions [2–6], adaptation aims to decrease the other harmful effects of climate change [7,8].

This topic is vital since contemporary cities were not designed with climate change in mind. Urban geometries, surfaces, building forms and envelopes (wall, roof, floor, physical characteristics such as insulation, glazing ratio, etc.) were designed according to organizational and aesthetic ideals rather than to adapt to climatic changes, which is only becoming an issue nowadays [9,10]. To mitigate and adapt, building envelope alteration is one logical type of intervention. Such kinds of operations are proposed and encouraged in the Swiss Energy Strategy 2050. This option is studied in this paper with the case of reference the campus of Ecole Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland.

### 1.1. Changing Climate and Changing Buildings

It is common knowledge that the properties of materials used in building envelopes and the insulation values play an essential role in the thermal response and environmental impact of buildings. Primarily two effects must be considered: (1) the envelope characteristics directly affect the heating and cooling loads generated to ensure indoor comfort; (2) the envelopes constitute an essential element in an urban site, transforming the microclimate, which in turn has a substantial impact on building energy demand and outdoor and indoor comfort [11–13]. It is thus sensible to explore envelope characteristics in a mitigation strategy for climate change and to exploit their direct and indirect effects on indoor comfort [14].

Buildings are important components of the built environment, influenced both by the long- and short-term changes of climate [15,16]. Building energy demand will change in response to future climate change, with cooling and heating demand going in opposite directions. Net increases or decreases largely depend on a region's cooling or heating demand dominance [17]. It is thus key to understand how local climate change affects building energy demand distinguishing between heating and cooling. Furthermore, it is critical to have a look at hourly data, as well as the peak demand (for peak demand is the most critical factor in the long-term planning of energy systems) [18,19]. Several impact assessment studies were conducted on buildings, with regard to the future energy demand and challenges [20–22], retrofitting buildings [23–25], as well as wind loads, rain and the microclimate [26–29].

### 1.2. Urban Simulation Workflows for Climate Change

Multiple tools have been developed in recent decades for a broad range of applications to produce regional data for future scenarios or to address sustainability in urban areas. For example, some studies have used a combination of techniques (dynamic and statistical models) to downscale outputs from a global climate model to produce useful regional climate change simulations or datasets [30,31]. Remote-sensing methods that analyze land use cover and land use changes while monitoring meteorological variables can also be used to understand local dynamics and processes [32–34]. However, these cannot be easily extrapolated for future scenarios and multiple locations [32]. Others have used regional climate models or meso-scale meteorological models (for example, the Weather Research and Forecasting model (WRF [35]), the MESOScale Non-Hydrostatic model (MESO-NH [36])), including parameterizations such as the Building Effect Parameterisation - Building Energy Model (BEP-BEM [37–39]), or the Town Energy Balance (TEB [40]), or the Urban Canopy Model (UCM [41]), that would better show the influence of urban areas on meteorological variables. These developments were an important leap forward for the representation of the urban heat island phenomena [42,43]. Nevertheless, the models employed cannot work with a very high horizontal resolution ( $\sim$  m) due to a lack of physical schemes that are appropriate for resolving the flow at such a resolution [6,43–45] and are very costly (regarding computational time) when producing yearly simulation with an hourly time step [46].

Other micro-scale models such as CitySim [47] or Envi-Met [48] have more detailed radiative transfer calculations. The advantage of using these models is that they provide an enhanced description of the surface. Envi-Met, for example, is used to perform microclimatic studies of the flows around buildings [49], but it cannot take periodic boundary conditions into account and thus can deviate from reality after 1–2 days. CitySim can be run for 8760 hourly time-steps, but it does not take into account local airflows and hence lacks a proper description of the micro-climate so particular to urban areas.

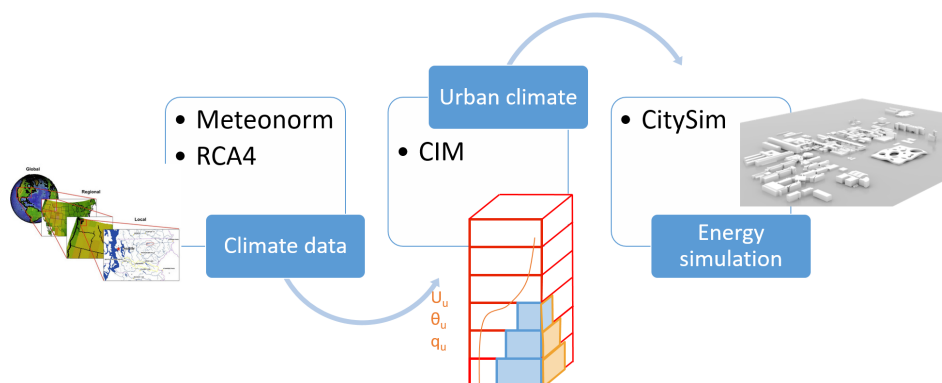
One of the most efficient and most common methods to overcome the limitations described above is the coupling approach, which links inputs and outputs. In recent years, some attempts have been made to couple meteorological models with building energy models [50,51]. Outdoor environments with high wind speeds with complex flow patterns are modeled with computational fluid dynamics (CFD) tools. CFD models have therefore been used to provide a better description of the air flows around buildings [52–54]. These models require significant computational resources and are not practical for the evaluation of urban planning scenarios. Mauree et al. [55,56] have therefore developed an urban canopy model, the canopy interface model (CIM), to provide high-resolution vertical profiles to building energy models. In a previous study, they validated the coupling of CIM with CitySim and demonstrated the advantage of the coupling in the simulation of building energy use in an urban district [57].

Although some recent studies have developed new coupling methodologies for urban simulation [8,57–60], there is still a need to evaluate multiple scenarios, as well as the annual performance of the coupling in the context of climatic change. A proper set of predicted climatic data should be used to produce future climatic scenarios adapted to urban areas and to determine the relevance of using the multi-scale coupling to provide meaningful information to urban planners. The objective of this paper is two-fold: (1) to understand the impact of climate change and of the future local climatic conditions on the energy demand of buildings, as well as its sensitivity to envelope characteristics; (2) to propose an urban simulation workflow and discuss its implications.

The paper is structured as follows: In Section 2, a short description of the different tools used is given. We explain how future climatic data were generated, how they were used as input for CitySim to calculate the surface temperatures and then used as boundary conditions for CIM. We then show in Section 3 how the wind speed and air temperature differ in an urban context and how relevant this is to use local climatic data in the evaluation of energy consumption. We consequently demonstrate the resilience of the built areas with a refurbishment scenario for the future climate. To conclude, Section 4 discusses the implications of the simulations and the results on energy system sizing, as well as on urban design.

## 2. Materials and Methods

In this section, a brief description of the different methodologies used to create the dataset for the energy simulation tools, as well as the building energy model is given. Figure 1 illustrates the process of energy consumption simulation at the district scale.



**Figure 1.** Schematic illustration of the flow of the simulations (CIM - Canopy Interface Model).

### 2.1. Preparation of Climate Files for Future Scenarios

Two major types of future weather datasets, to be used in impact assessment of climate change, are created using statistical or dynamical downscaling of global climate models (GCMs), each with their advantages and disadvantages, as discussed in some publications [15,61–63]. Outputs of RCA4, the fourth generation of the Rossby Centre regional climate model (RCM) [64], are used in this work, dynamically downscaling five different climate scenarios. One major challenge in working with future climate data is dealing with uncertainties induced by different climate models, emissions scenarios, initial conditions, etc. [16,21]. For a valid assessment of probable future climatic conditions, it is essential to consider several future climate scenarios. More information is available about the climate scenarios and on the calculation of some of the climate parameters in [61,65], respectively. A valid impact assessment should consider several climate scenarios for periods no shorter than 20–30 years. In the current study work, the assessment was made for three periods of 2010–2039, 2040–2069 and 2070–2099. Consequently, another major challenge in the impact assessment of climate change will be dealing with large datasets (as discussed thoroughly in some previous works [21,65,66]). This results in enormous calculation loads, especially when microclimate, retrofitting of buildings and sizing of the energy system are considered. To overcome the computational challenges, while not neglecting extreme climatic conditions, representative weather datasets are generated as described by Nik [65]. In this method, each 30-year period is represented by three one-year weather datasets: typical downscaled year (TDY), extreme cold year (ECY) and extreme warm year (EWY). The application of the method has been verified for energy [65,67] and hygrothermal simulation of buildings [68]. A more detailed description of the preparation of the climate data for building simulations is given by Nik [61]. For the purpose of this study, we will use the typical downscaled year.

### 2.2. CIM

CIM is an urban canopy model that can be used in an offline mode to provide high resolution data for building energy simulation tools [56]. It has already been coupled with CitySim to take into account the particularities of urban areas and to improve building energy simulations [57]. CIM is a column module where the Navier–Stokes equations are reduced to one dimension. Flow is resolved for the two wind components in the horizontal direction and also the air temperature along the vertical axis.

$$\frac{du}{dt} = \frac{d}{dz} \left( \mu_t \frac{du}{dz} \right) + f_u^s \quad (1)$$

$$\frac{d\theta}{dt} = \frac{d}{dz} \left( \kappa_t \frac{d\theta}{dz} \right) + f_\theta^s, \quad (2)$$

where  $u$  is the mean horizontal velocity ( $\text{m s}^{-1}$ ),  $\theta$  is the potential temperature (K),  $\mu_t$  and  $\kappa_t$  are the momentum and heat viscosity coefficients (calculated using a 1.5 turbulence closure) and  $f_u^s$  and  $f_\theta^s$  are the source terms representing the fluxes that will impact the flow.

Additionally, CIM resolves its own equation for the turbulent kinetic energy providing an enhanced description of turbulent flow over complex terrain while not significantly using computational resources. More details can be found in Mauree et al. [56].

### 2.3. CitySim

The urban energy modeling tool, CitySim [47,69,70], is used to calculate energy demand at the neighborhood scale. It proposes a simplified resistor-capacitor network as an analogy for the thermal representation of building behavior. A radiation model based on the simplified radiosity algorithm (SRA) is incorporated in CitySim. In the model proposed by Robinson and Stone [71], two hemispheres are used to represent the radiant external environment. CitySim can simulate both the demand



(electricity and heating) and the supply (for example, from solar PV panels). The software dynamically computes these outputs with an hourly time step while also taking into account inter-reflections between building surfaces and shading from other obstacles. The meteorological information is usually extracted from the Meteonorm software [72] where typical meteorological years can be obtained. These input data can be replaced with on-site monitoring where available. Walter and Kämpf [73] validated the software with the Building Energy Simulation Test (BESTEST), and Mauree et al. [57] in a previous study also compared the demand from the simulation with actual energy consumption. Upadhyay et al. [74] and Coccolo et al. [75] have recently included the evapotranspiration from the ground surfaces in the model and evaluated the outdoor human comfort [76].

#### 2.4. Study Case

The campus of EPFL is chosen as the study case (see Figure 2a). Covering an area of 55 ha, the campus is comparable to an urban area, with over 10,000 students and 5000 staff members. It is already an experimental site with a 2-MW power plant from the integration of photovoltaic panels (Figure 2b). The energy model of the EPFL campus was previously defined and validated with on-site monitoring, focusing on its current and future thermal behavior, as well as the microclimatic conditions within the urban environment [57,63,76,77]. The geometrical information of the campus was obtained from Carneiro [78], and the physical data of the buildings were defined according to the phase of construction. In the current paper, the energy simulations are done for the existing EPFL campus to quantify the impact of the changing climate on the energy consumption of the built stock and the importance of taking urban climate into account. Hence, two set of simulations are performed with CitySim with scenarios issued from (1) RCA4 and (2) RCA4-CIM. This means that either the RCA4 data are used to simulate the energy consumption with CitySim and secondly by including the urban effect with an additional simulation with CIM. A total of six simulations are performed: 2039, 2069, 2099, 2039-CIM, 2069-CIM and 2099-CIM.



(a) Map of the EPFL campus

Figure 2. Cont.



(b) Integration of PV panels on the site

**Figure 2.** (a) Top view of the Ecole Polytechnique Fédérale de Lausanne (EPFL) campus, Switzerland, from Open Street Map (copyright notices can be found here: <https://www.openstreetmap.org/copyright> (CC-BY-SA-2.0)) and (b) example of PV integration on the EPFL campus (Alain Herzog/EPFL).

### 2.5. Renovation Scenarios

As stated above, one of the objectives of this paper is to understand the impact of climate change and the future local climatic conditions on the energy demand of buildings, as well as its sensitivity as a function of the envelope characteristics. Simulations of a hypothetical refurbishment of the university campus according to the high energy efficiency standard Minergie-P were performed [77]. Minergie [79] is a well-established standard, commonly applied to the Swiss construction market; a stricter standard is Minergie-P, which targets a lower energy demand. To use the standard, all buildings are well insulated with 35 cm of expanded polystyrene (EPS) and triple glazing with an infrared coating. The novelty in the proposed approach is the fact that the Minergie standard is applied to an entire campus, not only to one building and the simulations are performed till the end of the 21st Century to determine whether these standards are sufficient to reach the goal set by the Energy Strategy 2050.

## 3. Results

Table 1 summarizes the simulations that have been run for the different climatic scenarios. The results from these runs are described hereafter.

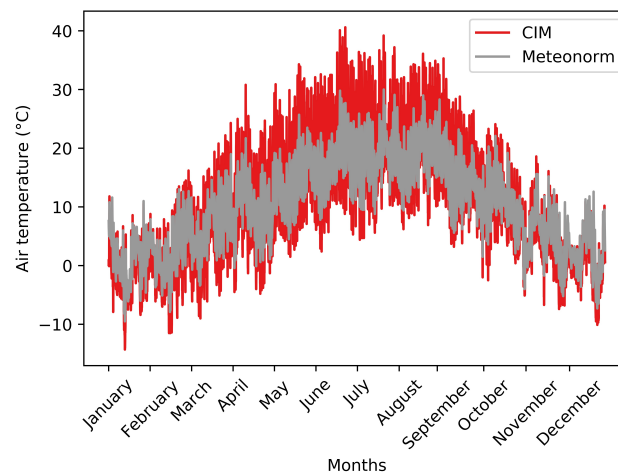
**Table 1.** Set of scenarios.

Years	Meteonorm	CIM	Renovation
2039	X	X	
2069	X	X	
2999	X	X	X

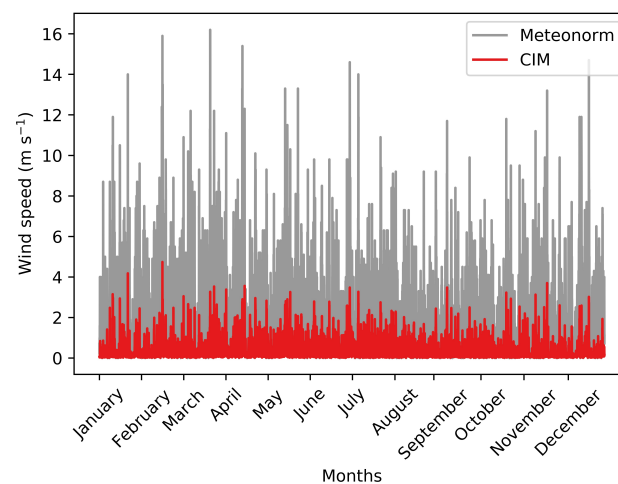
### 3.1. Analysis of the Future Climate in an Urban Context

The first simulation is performed with the typically used dataset obtained from Meteonorm. The wind speed and air temperature are averaged climatic values (from 1990–2010) for the location

of Ecublens. Figure 3 shows values for each time step through the year for the data obtained from Meteonorm and the one produced by CIM.



(a)



(b)

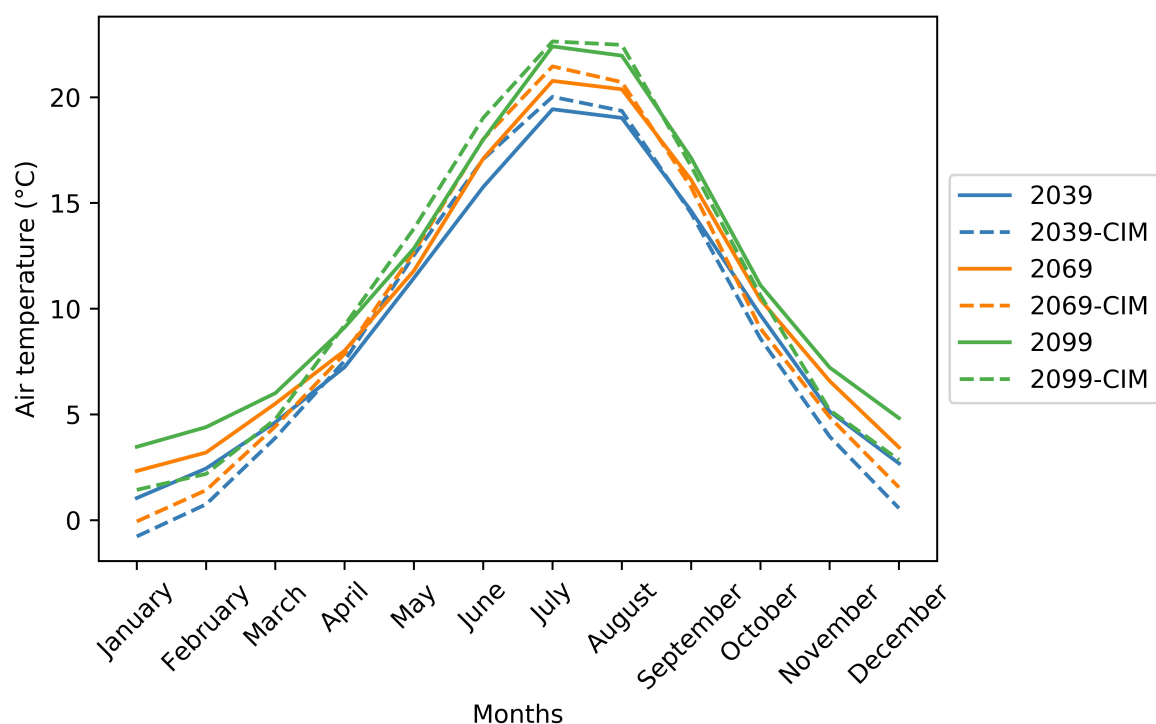
**Figure 3.** Changes between the Meteonorm and CIM dataset for the (a) air temperature (°C) and (b) wind speed (m s<sup>-1</sup>). Adapted from Mauree et al. [57].

Table 2 summarizes the statistical analysis conducted for these two datasets. It is clear that there is a notable difference between the two scenarios. For example, the mean wind speed is decreased from 1.94 (m s<sup>-1</sup>) to 0.37 (m s<sup>-1</sup>), while for the air temperature, there is a decrease from 10.3 °C–9.9 °C. It should be highlighted that the CIM model yields a lower mean annual air temperature, and the maximum temperature is significantly higher (>10 °C) when considering climatic conditions of the local environmental.

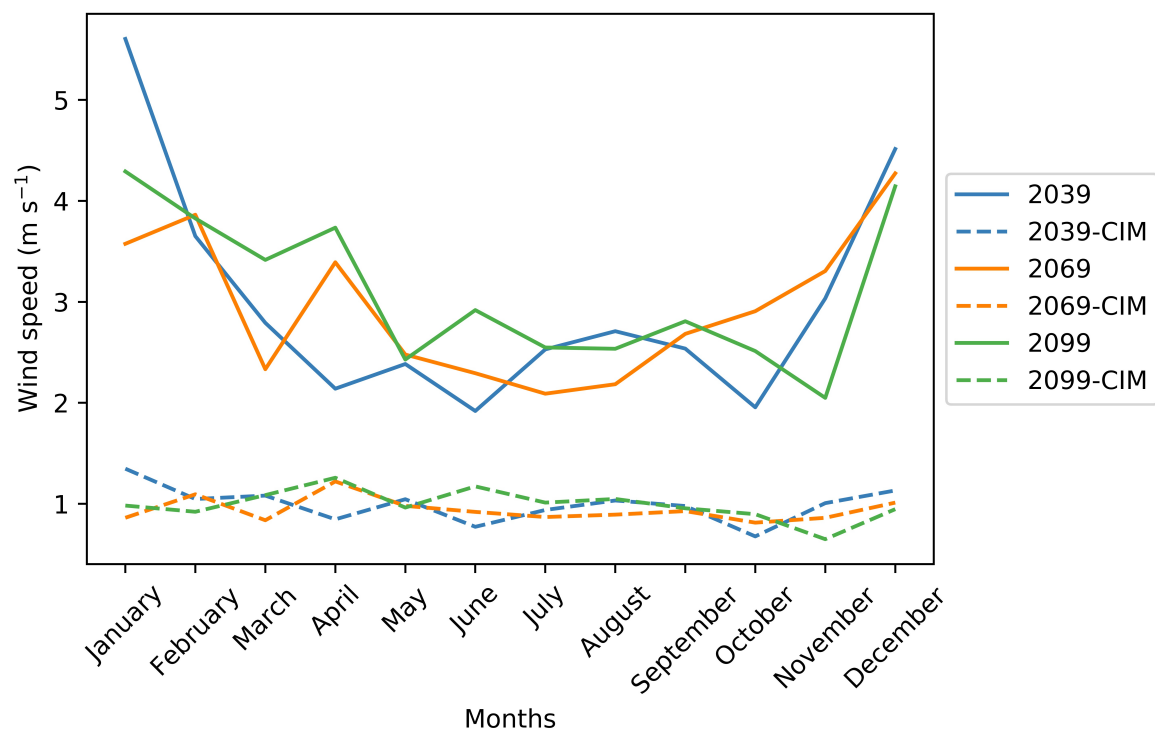
**Table 2.** Statistical analysis of the variables for a typical year (averaged over the period 2000–2010) from Meteonorm and CIM.

	Wind Speed ( $\text{m s}^{-1}$ )		Air Temperature ( $^{\circ}\text{C}$ )	
	Meteonorm	CIM	Meteonorm	CIM
Mean	1.94	0.37	10.28	9.92
St. Dev.	1.94	0.48	7.74	9.97
Min.	0.00	0.02	−9.50	−14.30
Max.	16.2	4.74	30.00	40.60

Figures 4 and 5 show the monthly averaged temperatures and wind speed respectively for the three climatic scenarios of the future. The air temperature increase is evident both with and without CIM, with a slightly higher rise during the summer periods. On average, CIM yields a lower mean annual temperature, but notably higher maximum temperature ( $0.6^{\circ}\text{C}$  in 2039,  $0.7^{\circ}\text{C}$  in 2069 and  $0.2^{\circ}\text{C}$  in 2099). There are no clear trends in the wind speed when looking at the change in the future for the monthly mean values. It can nonetheless be noted that the wind speed in the 2039 scenarios appears to be higher during the winter time compared to the other two cases. As Mauree et al. [57] have shown, the energy demand of buildings is tightly related to the local microclimate. This impact will be further explored for the future climate in the next sections.



**Figure 4.** Change in air temperature ( $^{\circ}\text{C}$ ) for 2039, 2069 and 2099 without CIM (full line) and with CIM (dashed line).



**Figure 5.** Change in wind speed ( $\text{m s}^{-1}$ ) for 2039, 2069 and 2099 without CIM (full line) and with CIM (dashed line).

### 3.2. Energy Consumption for the EPFL Campus

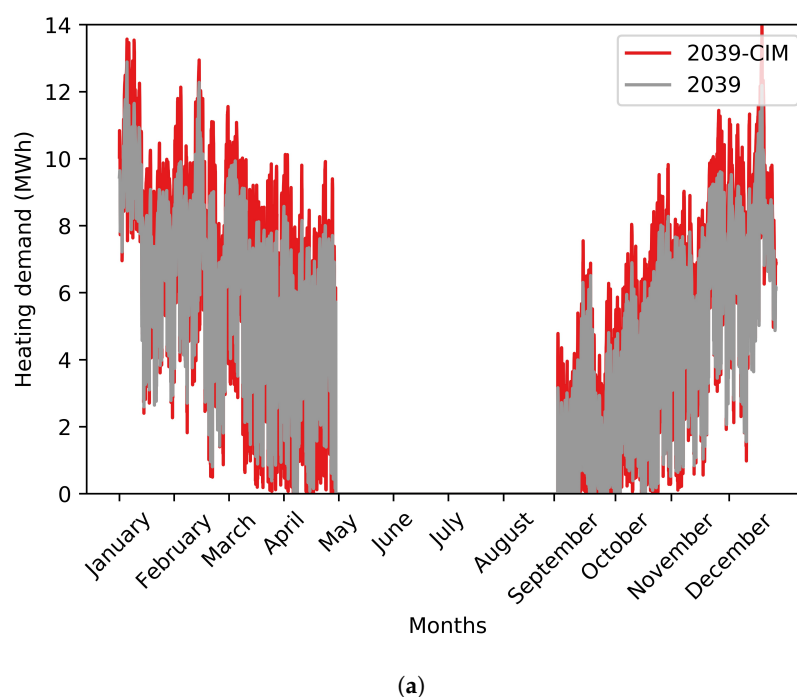
Both climatic and microclimatic data significantly influence the energy demand of a site. Table 3 summarizes the total heating and cooling demand of the campus, according to the future climatic conditions 2039, 2069 and 2099, as well as the microclimatic weather data, as computed by the canopy interface model (2039-CIM, 2069-CIM and 2099-CIM). With rising temperatures, the heating demand decreases in the future climatic scenarios, by 7% and 15% according to the climatic data for 2069 and 2099, respectively (when taking 2039 as the baseline). However, when simulating with CIM microclimatic data, the total heating demand decreases less, by 5% and 12% (for 2069 and 2099, respectively). Additionally, when simulating with CIM microclimatic data, the heating demand appears higher compared to the climatic data: this is due to the so-called cool air pool effect, related to the density of the urban environment that characterizes the site [57]. When looking at the cooling demand, the campus will face an increase of 30% and 52% in 2069 and 2099, respectively. When considering the microclimate, the increase although still significant is reduced to 20% and 36% for 2069 and 2099, respectively. Overall, it can be noticed that there is a considerable underestimation of both the heating and cooling demand when the urban microclimate is neglected.



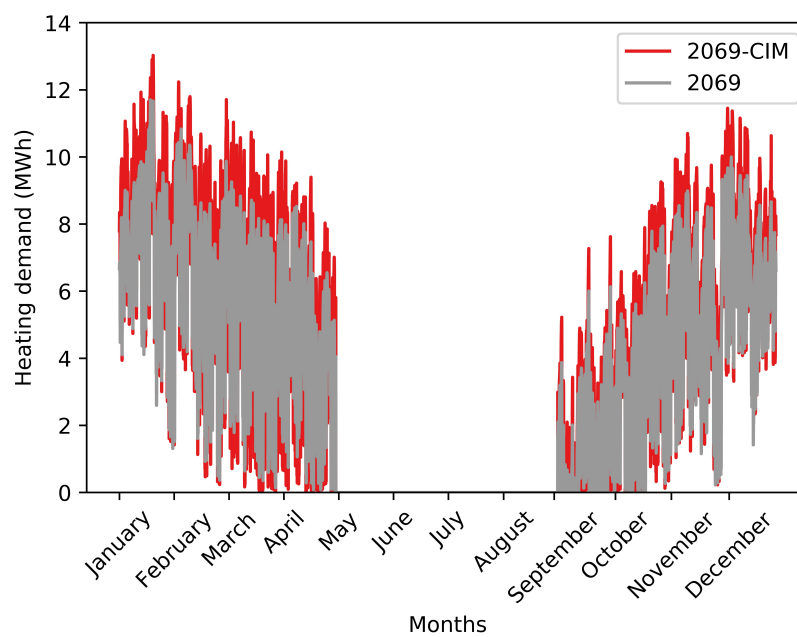
**Table 3.** Energy demand of the site for all scenarios. Values are positive for the heating demand and negative for the cooling demand.

Climatic Data	Heating Total Demand (GWh)	Cooling Total Demand (GWh)
2039	32.42	−2.79
2069	30.19	−3.99
2099	28.05	−5.83
2099-MinP	18.41	−9.62
2039-CIM	35.22	−5.81
2069-CIM	33.52	−7.26
2099-CIM	31.33	−9.12
2099-MinP-CIM	21.29	−14.60

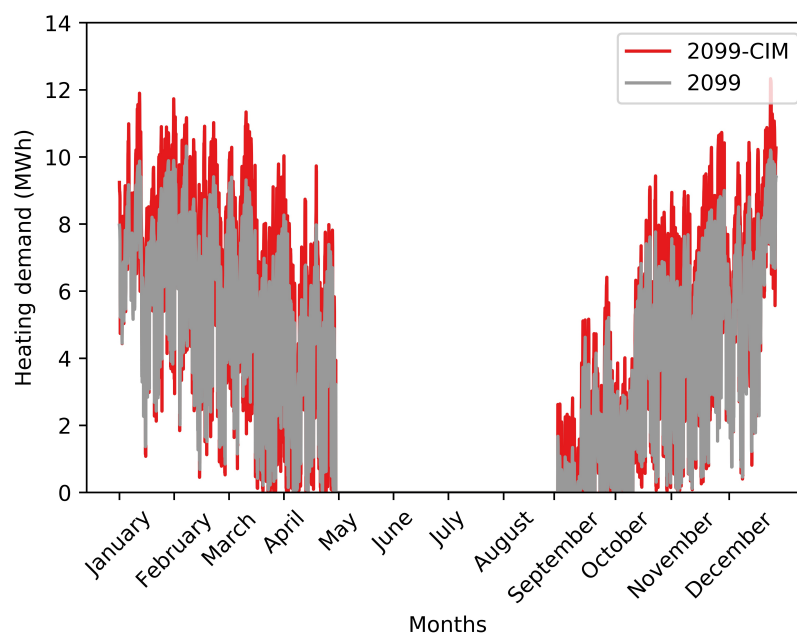
Figure 6 shows the hourly total heating demand, as calculated with the RCA4 and RCA4-CIM data, for each year of simulation. It can be noticed that there is a higher variability of the heating demand when taking into account the local climate. For example, the standard deviation demand for the 2099 scenario is 2.8 MWh, while for the 2099-CIM scenario, it is 3.3 MWh. All the other scenarios (both for the cooling and for the heating demand) showed similar trends. Figures 7 and 8 illustrate the difference in the demand generated by CitySim for 2099 with and without CIM and demonstrate the divergent behavior of some particular buildings on the campus when accounting for the local climate. It can be noticed that the heating demand for the buildings increases, by about 3 kWh/m<sup>2</sup>, in the denser part of the campus. It should also be highlighted here that the simulations suggest a higher heating demand over the campus when taking into account the local climatic data from CIM. The lower temperatures during the winter months as shown in Figure 4 could be an explanation for this behavior. Indeed, when looking at a group of buildings (particularly in a dense area), in the winter time at mid-latitude, the solar angle is relatively low, and thus, there are less solar gains. This is not captured in typical climatic data, but can only be obtained when taking into account the local environment, especially for the denser part of the campus.



**Figure 6.** Cont.



(b)

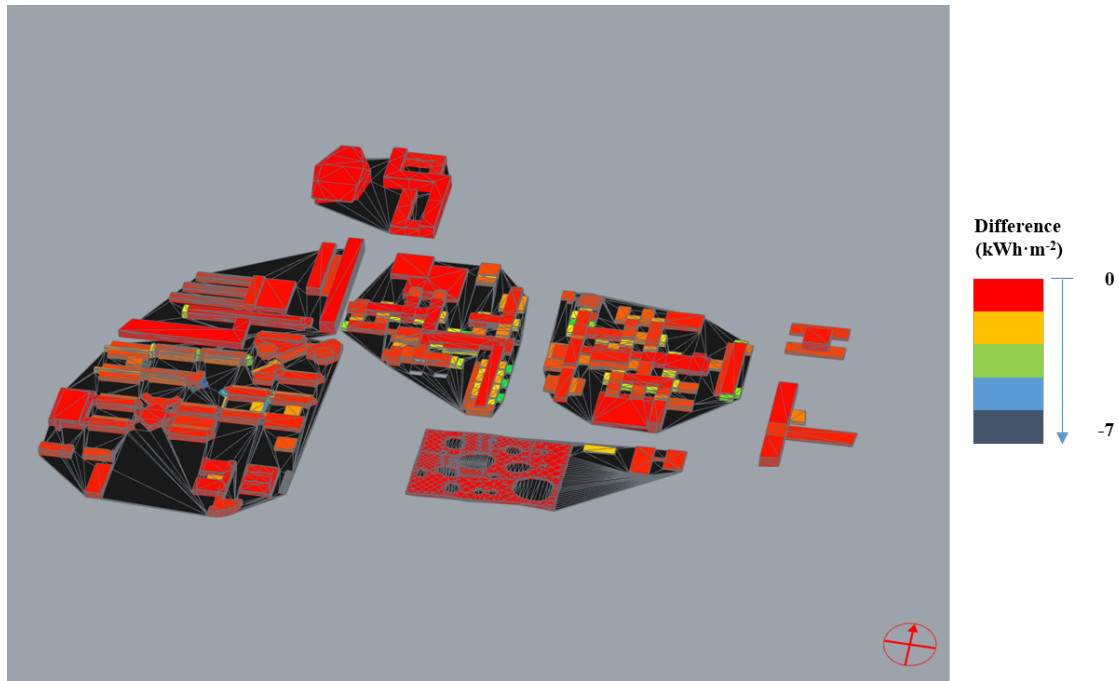


(c)

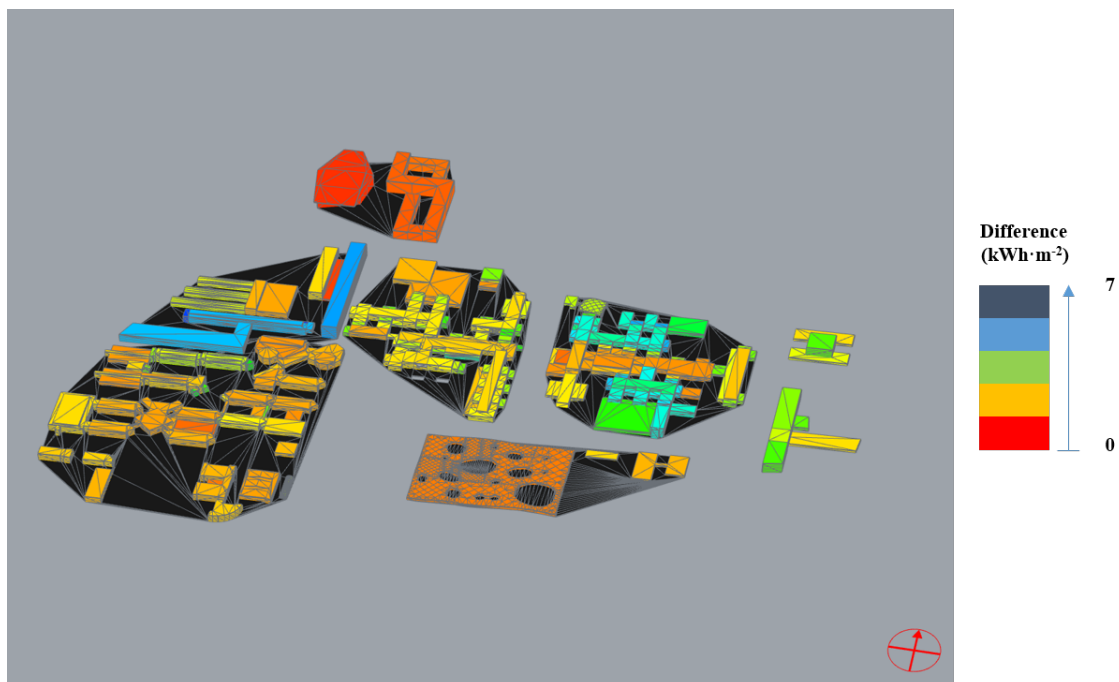
**Figure 6.** Heating demand for (a) 2039, (b) 2069 and (c) 2099 using the standard climatic data and the CIM data. Demand is given with an hourly time step.

To better understand the impact of microclimatic modeling on the thermal behavior of the campus, further analysis is performed on the peak demand of the campus. Table 4 summarizes the peak demand for heating and cooling for each of the scenarios. It can be observed that there are substantial differences between the peak demands. From the simulations, it can be seen that the rise in temperature due to climate change will be mostly responsible for an increase of 25% in the peak cooling demand (w.r.t the 2039 scenario). This is accompanied by a decrease (25%) in the peak demand for heating. When considering the local microclimate, the peak demand for the cooling needs rises by about 23%.

This suggests that the cumulative effect of the rise in temperature and the inclusion of the urban microclimate in the simulation of the cooling energy demand leads to an increase of 42% in the peak demand. On the other hand, the peak heating demand for 2069 and 2099 with CIM increases by 10% and 16% (w.r.t the 2039 scenario). These increase in the peak demand will have a significant effect on the energy system sizing, as was demonstrated in previous studies [18,80].



**Figure 7.** Map of the difference in heating demand for the EPFL campus for 2099 without and with CIM.



**Figure 8.** Map of the difference in cooling demand for the EPFL campus for 2099 without and with CIM.

**Table 4.** Peak energy demand of the site for all scenarios. Values are positive for the heating demand and negative for the cooling demand.

Climatic Data	Heating Demand (MWh)	Cooling Demand (MWh)
2039	12.9	−10.4
2069	11.7	−14.4
2099	10.3	−13.9
2099-MinP	7.5	−16.7
2039-CIM	14.0	−14.5
2069-CIM	13.0	−18.0
2099-CIM	12.3	−18.1
2099-MinP-CIM	9.0	−21.4

### 3.3. Renovation Scenario

Further analysis is performed to quantify the impact of a hypothetical renovation scenario, according to the Minergie-P label, and its sensitivity to the climatic data. In the previous analyses, we have seen that the selection of climatic or microclimatic data impacts the calculated energy demand of the site, with an annual variation of circa 10% (comparing the heating demand as quantified by the climatic and CIM data, for each year). It is quite interesting to notice that the difference is slightly higher when working with well-insulated buildings; indeed, when comparing the 2099 climatic data, the difference corresponds to 14%. Table 3 also gives the heating and cooling demand with these two scenarios. It can be highlighted that on the one hand, there is a non-trivial decrease (76%) in the heating demand, but that on the other hand, the cooling demand is increased by the same order of magnitude (71%). It is also noteworthy to mention that the difference varies as a function of the month; as an example, it corresponds to 33% during September and to 10% during April. Additionally, if the peak demand is considered (see Table 4), significant differences are noted between the base case (2039) and the renovation scenarios (with and without CIM).

## 4. Discussions and Conclusions

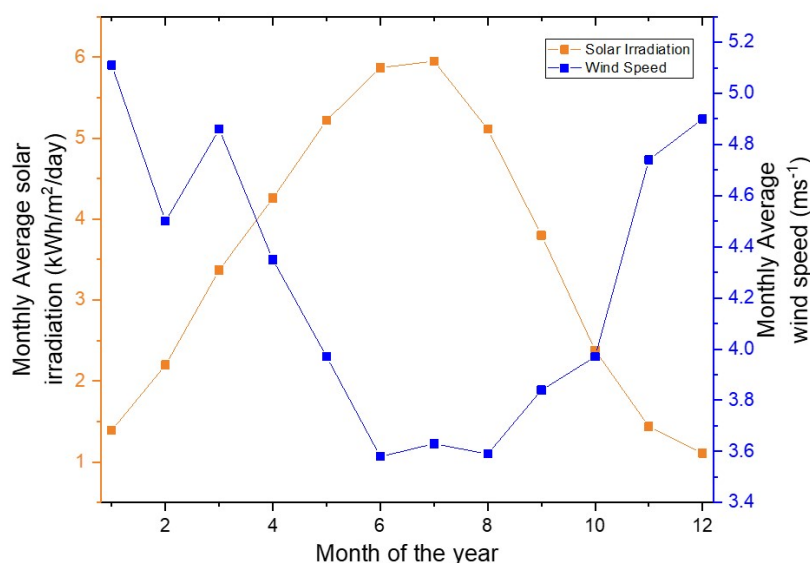
### 4.1. Impact of Considering the Urban Microclimate

The results presented in Section 3 demonstrated that taking into account climate change in future energy simulation is not sufficient. Local microclimatic data must also be taken into account in the design of more sustainable urban areas. The results often showed unexpected behavior due to the non-linear and complex processes found in urban areas. Firstly, it was evident that the calculated demand is fluctuating more when using the canopy interface model, than when using the standard climatic data. This is directly related to the physical properties of the built environment, which impact the thermal behavior of buildings. As expected, this impact varies both in time and space: according to the urban geometry, as well as during the day-nighttime cycles. During daytime, the urban surfaces (due to their thermal and physical properties) create a hotter environment than rural areas, hence increasing the air temperature. During the nighttime, some areas of the campus refresh faster than others (due to their high sky view factor), consequently creating several microclimatic conditions within the site. Other studies should be conducted with additional tools to verify the results we have shown and to assess the urban energy consumption. When looking at the renovated scenarios, it can be seen that the annual difference in the energy demand (around 14%) when taking the local microclimate into account is similar to previous studies [57]. The study raises some questions relating to the future transition pathways. Indeed, it can be highlighted that the current renovation scenarios are not adapted to decrease the overall energy consumption. This will have significant impact on the energy system sizing and also on the greenhouse gas and anthropogenic emissions in urban areas. We further discuss the implications in the next paragraphs.

## 4.2. Energy System Design

Deriving the energy demand for the buildings is the first step in calculating the energy demand of the campus. It was demonstrated in Section 3 that there will be significant fluctuations and increase in the peak demands. If no actions are taken, this can lead to unintended consequences on the energy system. Time series of the hourly demand profile for heating and cooling should be accurately calculated in this context. Combining urban climate and building simulation models are important [18]. Similarly, renewable energy potentials for installation of wind turbines and solar PV/thermal should be considered to evaluate the potential of integrated renewable energy technologies [81].

The main campus site of EPFL is blessed with both solar and wind energy. Monthly energy potentials for both these energy sources are presented in Figure 9. When analyzing Figure 9, it is clear that the energy potential for wind speed is complementary to the solar energy potential. The solar energy potential is higher during the summer, while the wind energy potential is higher during the winter. EPFL already has a roof-top-installed solar PV park with a capacity approaching 2 MW of peak power. However, there are no wind turbines installed. The campus benefits from the adjacent Lake Geneva when it comes to heating. Heat pumps are used to heat up the water of the lake during moderate winters. Co-generation gas turbines, which generate both heat and electricity, are used during the intensive winters, and fossil fuels are used to power up the gas turbines. The peak heating demand at present is 32.42 MW, which is expected to decrease continuously due to climate change. In contrast, cooling peak power is expected to grow continuously up to 21.4 MW. This makes it essential to bring up notable changes to the energy systems. Absorption chillers might have to be introduced in order to cater to the cooling demand using gas turbines. However, use of gas turbines would not be the best solution due to its carbon impact.



**Figure 9.** Fluctuations in monthly average energy potential for wind speed (at the height of 50 m) and solar irradiation.

Renewable and sustainable energy solutions can be used to replace the contribution of gas turbines. Building-integrated wind turbines will be an effective solution in this context, as they have a higher energy potential during the winter. Energy storage might be required to support such an extension to the renewable energy integration within the campus site. EPFL already hosts a 720 kVA/500 kWh battery storage system. However, energy storage should be extended further to facilitate renewable energy integration while maintaining system autonomy. It is important to quantify the requirements for energy storage, renewable energy components and the other energy conversion devices. This can



be achieved with energy system design tools [80] and based on principles proposed by Vandevyvere and Stremke [82].

#### *4.3. Improved Urban Design and Future Transition Pathways*

The overall analysis that does not consider the retrofit strategy concludes that annual cooling energy consumption is likely to increase by a few percent, while heating energy consumption (using a variety of fuels) will reduce by a few percent. There would undoubtedly be a shift towards electrical power demand. If no intervention is undertaken, higher energy use in buildings will lead to more substantial emissions, which in turn will exacerbate climate change and global warming. In this study, we have evaluated the impact of climate change on the energy demand, as well as one commonly-used standard in Switzerland, Minergie-P. This renovation is part of the mitigation strategies to decrease the energy footprint of buildings and urban areas in general. Although the standard addresses a number of parameters to reduce the carbon footprint, one of its main components is the insulation and the tightness of the building. In our study, this measure showed no potential to mitigate the energy consumption and by extension the greenhouse gas emissions.

The cooling demand is increased, and given its cost, it is worth challenging the strategy proposed by Minergie of further increasing insulation levels. With climate change in mind, this approach needs to be revised to manage the cooling scenario. Given the high “architectural value” of several of the buildings on the EPFL campus, a further study is necessary to understand which buildings should be retrofitted. Typical facade retrofitting solutions cannot always be applied at EPFL, where the exterior of buildings cannot be modified due to the needs of preservation of the original design. The non-invasive transformation of existing buildings should look at nanoscale solutions that can change the reflectivity, emissivity and absorptivity of facades.

Time-varying interactions with local microclimate conditions impact the design of heating and cooling systems; changes in the surrounding climate conditions affect building energy consumption. Thinking of a retrofit scenario, it would be essential that the envelope performs for the environments that it faces: inside and outside. While this paper focuses mainly on the energy required to achieve comfort according to Minergie’s prescriptive targets, further attention should be dedicated to achieving a microclimate that mitigates cooling loads. This means the development of envelope solutions that reduce shortwave and longwave thermal exchanges, creating a cooler environment where the buildings stand.

Sensitivity studies should clarify whether intervention on the building envelope or intervention on the outdoor surfaces is more effective in reducing building cooling loads [4]. It will be verified whether an individual envelope strategy can neutralize the increases in cooling energy usage or a combination of several site-based passive strategies may counteract the effects of climate change on cooling energy usage. The EPFL configuration, characterized by a very high sky view factor that affects short-wave and long-wave solar radiation on construction surfaces, can produce massive outdoor local overheating. Further interventions should thus aim at reducing the campus heat island. Additionally, the study should compare the impact of added vegetation [75,83] and selective urban materials to envelope measures.

While measures for remodeling building envelopes in response to climate change were one focus of the paper, to devise adequate countermeasures for existing buildings, it is essential to understand how the energy consumption behavior of a building may interact with the local microclimate. To this end, more design strategies for building and site remodeling will be studied and their potential for mitigating the increases in cooling energy usage discussed.

#### *4.4. Perspectives*

The objectives of the present study were two-fold: (1) to downscale future climatic data while at the same time improving the meteorological boundary conditions used in energy simulation at the neighborhood scale; (2) to evaluate the impact of a current renovation standard on the building

energy demand in the future. Using previously developed tools, we have created a new framework with the aim of providing key information to urban planners, architects and engineers working on the sustainable design. Lundgren and Kjellstrom [84] previously mentioned that there was a lack of studies to link localized climate to energy demand, especially cooling, in urban areas and that this was crucial for the adaptation of urban areas in response to the current climate change while also decreasing their carbon and energy footprint. The novelty of our approach is its ability to calculate annual energy consumption at an hourly scale with reasonable computational resources. This is a key aspect in the evaluation of multiple planning scenarios and for the definition of sustainable transition pathways. We have demonstrated that without a full annual simulation, we would lack information that is critical for the design of energy systems, and this would have significant implication in the climate change mitigation strategies. However, there is still a need to evaluate the developed framework in multiple other locations to test its reliability and robustness. A two-way coupling between CIM-CitySim could also provide enhanced boundary conditions for both models. Additionally, one aspect that could also be addressed using the output from this study is outdoor human comfort. Other future studies should furthermore look at the implication of sustainable urban design on society. Williams et al. [85] already pointed out that this was crucial for the best implementation of the solutions, but that there was a need for “better understanding the problem by a variety stakeholders”. This study hopes to reduce this knowledge gap by providing a new methodology that should be extended to multiple other cities and different urban configurations and climatic regions.

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